

Summary of Invited Paper
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Cryogenic MMIC Low Noise Amplifiers

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Abstract

Monolithic (MMIC) and discrete transistor (MIC) low noise amplifiers are compared on the basis of performance, cost, and reliability. The need for cryogenic LNA's for future large microwave arrays for radio astronomy is briefly discussed and data is presented on a prototype LNA for the 1 to 10 GHz range along with a very wideband LNA for the 1 to 60 GHz range. A table of MMIC LNA and mixer designs under development for the frequencies up to 210 GHz is reported and data on cryogenic amplifiers in the 85 to 115 GHz is reviewed. The current status of the topics of transconductance fluctuations and cryogenic noise modeling will be briefly summarized.

MMIC vs MIC Comparison

As a starting point it is instructive to compare the advantages and disadvantages of monolithic microwave integrated circuit (MMIC) low noise amplifiers with microwave integrated circuit (MIC) amplifiers constructed with discrete chip transistors and passive microstrip circuit boards. A summary of this comparison on the basis of performance, frequency range, cost, and reliability follows.

Transistor Performance - The discrete transistors used in the MIC case are manufactured in the same manner as the transistors built into the MMIC amplifier and to a large extent this leads to the same expected performance. Two exceptions can be argued. In the MIC case, transistors can be selected to give the lowest noise; however the MMIC's can also be selected. To some extent the cryogenic low noise performance is correlated between different discrete transistors or MMIC's on a single wafer. With the order of 100,000 discrete transistors or 1000 MMIC's on a wafer, a larger number of cryogenic amplifiers can be built from one "golden" wafer. However, the need for very large numbers of cryogenic amplifiers has not yet occurred and could be met by processing a large number of wafers and selecting the best.

Passive Circuit Performance - A wider variety of passive circuit element values and quality factors are available to the MIC designer. However, in most cases the loss in a cryogenic passive circuit is negligible and a MMIC can use an external element such as an input inductor if it is necessary. It is possible to make shorter connections on a MMIC particularly the transistor source ground and this can help bandwidth and stability.

Frequency Range - The short connections possible with a MMIC become an important factor above 100 GHz. MMIC amplifiers with high gain at 215 GHz have been reported [1] but has not been achieved with MIC amplifiers. Multistage MMIC amplifiers operating below 500 MHz have difficulty with achieving sufficiently large coupling and bypass capacitors. DC coupling may be feasible in some cases but this restriction does not occur with MIC amplifiers utilizing multi-plate layer, high-dielectric constant capacitors.

Cost - The development cost of a MMIC varies between \$50K and \$500K dependant upon the processing cost for small mounts of wafer space for experimental circuits, the difficulty of the specifications, and the legacy of similar designs. The experimental processing cost is minimized

if several MMIC's are developed simultaneously or if most of the wafer space is paid by a production run. The production cost of a research quality wafer is of the order of \$100K and there are typically 1000 MMIC amplifiers per wafer, leading to a production cost of \$100 a chip. Module fabrication, assembly, and test make up a total cost of the order of \$1000. More labor is required to assemble and tune a MIC amplifier but this also varies widely with the difficulty of the specifications and experience of the technicians. A typical estimate may be \$2000 for the MIC amplifier. If we take \$200K as the development cost of a MMIC amplifier and \$50K to develop an MIC amplifier then the MMIC is less expensive for quantities over 150. During the next few years it may be expected that there will be MMIC LNA's available that are known to give good cryogenic performance and are available commercially off-the-shelf and hence can provide MMIC LNA's with no development cost.

Reliability - Reliable MIC amplifiers can certainly be constructed but the larger number of interconnections dependant upon human skill makes it easier to achieve reliability with a MMIC amplifier.

Wideband Microwave Amplifiers for Large Antenna Arrays

There are requirements for large numbers of very low noise cryogenic LNA's for large of antennas being designed or considered in the radio astronomy and space science communities as shown in Table I.

Table I - Future Arrays of Cryogenic Microwave Receivers.

Array	Purpose	Number and of diameter elements	Frequency Range	Present Status
SETI	Search for extraterrestrial intelligence	500 x 5m	.5 to 11 GHz	Hardware development
DSNA	Space communication	4000 x 5m	8 to 40 GHz	System study
SKA	Radio astronomy	TBD - 10 ⁶ m total area	.5 to 20 GHz	System study

The layout and measured noise performance of a MMIC amplifier designed for the 1 to 11 GHz range is shown in Figures 1 and 2. This amplifier is a prototype of an amplifier with a balanced input that is required for a wideband log-periodic feed that is being designed for the SETI array. To reduce cryocooler costs operation in the temperature range of 50 to 80K is being considered; the prototype amplifier has a noise temperature of <22K over most of the required frequency range even when operated at 80K. This noise is low but is several degrees higher than predicted on the basis of noise temperatures measured at 100 GHz with the same type of transistors [2].

MMIC LNA's for still wider frequency ranges are being developed either for use in very wideband systems or for IF amplifiers in millimeter wave or submillimeter wave receivers. MMIC amplifiers with instantaneous bandwidth covering the 1 to 60 GHz range have been designed, fabricated at both TRW and HRL foundries, and have been tested at room temperature with layout and results shown in Figures 3 and 4. The amplifier is coolable but in its present form dissipates about 50 to 150 mW of DC power at room temperature. A noise temperature of the order of 50K with power dissipation of 20 to 50 mW is expected at cryogenic temperatures.

It is important to note that both of the wideband amplifiers are designed to have low noise when driven from a 50 ohm source but do not have a matched input (i.e S11 approaches but is less than 1). The conventional methods of achieving both noise and input match (balanced amplifier, feedback, or isolators) become extremely feasible at bandwidths beyond one octave. The system performance penalty for the lack of input match is the sensitivity of gain to antenna impedance.

Millimeter Wave MMIC LNA's

A table of millimeter wave LNA's and mixers currently being developed at JPL is shown in Table II. Room temperature results for the 120LN1 and 200LN1 have been previously published [1,3] and most of the devices have not yet been tested at cryogenic temperatures

Table II – Millimeter Wave MMIC Designs Under Development at JPL

Type	Frequency Range	Foundry	Technology	Application
WBA5	.5 - 20 GHz	TRW,HRL	0.1um InP	Cryogenic IF Amplifier
WBA7	1 - 60 GHz	TRW,HRL	0.1um InP	Very Wideband, Low Power NA
40LN1 40LN5	35-60 GHz 25-60 GHz	TRW HRL	0.1um InP	LNA for Sensor
50LN1	45-65 GHz	TRW	0.1um InP	LNA for Atmospheric Array
53MIX1	49-57 GHz	UMS	GaAs Diode	I/Q Mixer
70LN1	50-75 GHz	TRW,HRL	0.1um InP	LNA for RadioAstronomy
86LN1A	75-120 GHz	HRL	0.1um InP	Airborne Imaging
105LN1	65-105 GHz	TRW	0.1um InP	Cryogenic LNA, Radio Astronomy
120LN1	100-140 GHz	TRW,HRL	0.1um InP	Atmospheric Sensing
120MIX1	90-140 GHz	UMS	GaAs Diode	Balanced Mixer
190LN1	180-200 GHz	Sanders	0.1um InP	Atmospheric Sensing
200LN1	170-210 GHz	TRW	.08 um InP	Atmospheric Sensing
200MIX1	170-210 GHz	UMS	GaAs Diode	2nd Harmonic Mixer

An array of 16 MMIC receivers (to be expanded to 32) covering the 85 to 115 GHz range has been constructed and is in operation on the 15m radio telescope of the Five College Radio Observatory of U. of Massachusetts [4,5,6] . These receivers utilize the 105LN1P as a first stage and the 86LN1A as a second stage. The noise and gain of both of the MMIC's at a temperature of 15K are shown in Figure 5 and an interior view of the WR-10 waveguide module containing either device is shown in Figure 6. More details are given in the referenced publications. Recent measurements at JPL of the gain and phase match of a pair of cascaded amplifiers with 35 to 40 dB gain has shown amplitude and phase match of 0.2 dB rms and 5° rms from 80 to 100 GHz.

Transconductance Fluctuations

The gain of all field-effect transistor (including HEMT) amplifiers randomly fluctuates as a function of time [7,8,9,]. This effect degrades the sensitivity of wide-bandwidth, slow-switched radiometers and may be a factor in AM noise of radar systems and phase noise in oscillators. The cause is believed to be due to carriers going into and out of traps in the semiconductor material. A summary of what is known is as follows:

- 1) The transconductance fluctuation, $\Delta G_m/G_m$, has a 1/F spectrum with values in the range of 5 to 50 parts per million at 1Hz for a 50 um wide transistor. This spectrum must turn over at some low frequency – perhaps 1 mHz since large gain changes are not observed over long periods (months) of time.
- 2) The fluctuation varies as the inverse square root of the width of the transistor.
- 3) The fluctuation appears to become worse by a factor of 2 to 10 at cryogenic temperatures.

- 4) The fluctuation is not strongly dependent upon the bias point. This is the case even if the device is biased at the peak of the transconductance vs gate bias curve where it is insensitive to gate bias.
- 5) The fluctuation is uncorrelated with drain current fluctuations. A constant drain current power supply with feedback controlled gate voltage does not reduce the fluctuation.

Noise Modeling

The Pospieszalski noise model [10] with gate noise, T_g , equal to ambient temperature, T_{amb} , and drain noise, $T_d = 300 + 6 * T_{amb}$, describes the measured noise of the lowest noise sample of the 105LN1P amplifier with a noise of the order of 30K at 100 GHz. This result is with the optimum bias for each temperature. However, the spread of cryogenic noise temperature even from chips from the same wafer is quite large, 30K to 60K, so that the T_d equation would be different for different transistors. There is much less variation in room temperature noise. MMIC amplifiers of type WBA5, made from the same wafer, as the 105LN1P appear to have higher noise by about 10K at $T_{amb} = 20K$ than is predicted by the above T_d equation. It is not known at present whether insufficient samples (only 2) have been measured or whether gate current noise is having an effect at cryogenic temperature.

A recent paper which calculates T_d using Monte Carlo methods at $T_{amb} = 300K$ and 15K finds that it is not very sensitive to temperature if the electric field is kept constant, i.e for constant bias, but T_d is lower at lower electric field. However at cryogenic temperature the drain voltage and drain current can be adjusted to be much lower without a large reduction in gain and this accounts for the reduction of T_d (the electric field is lower). Thus a theoretical investigation of optimum transistors for low cryogenic noise should include an understanding of the transconductance behavior at low drain bias and optimization of $T_d / (G_m^2)$.

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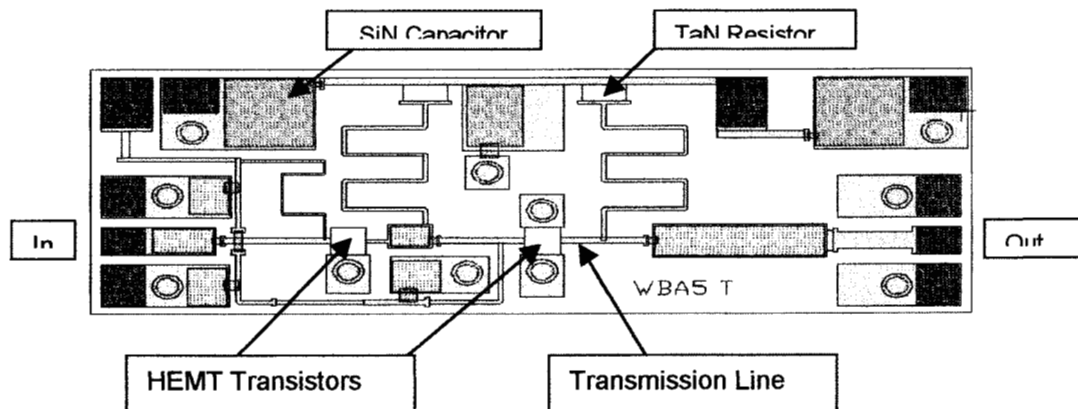


Figure 1 - Layout of MMIC 1 to 20 GHz LNA ; chip size is 2.0 x .74 mm.

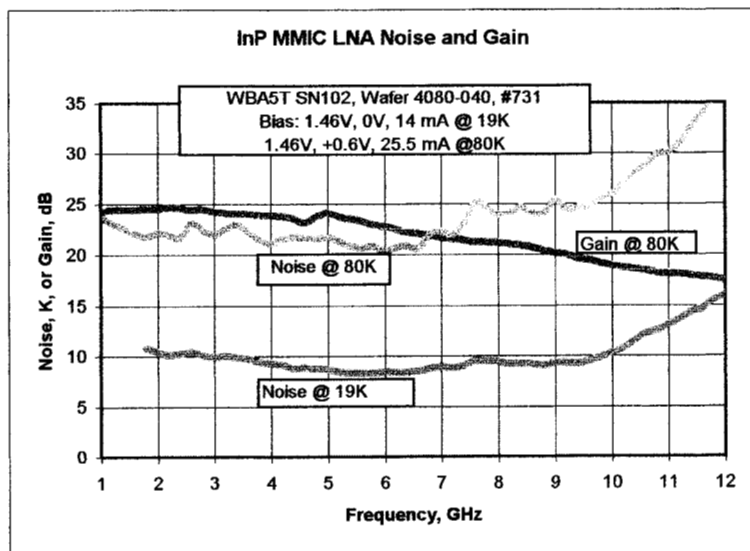
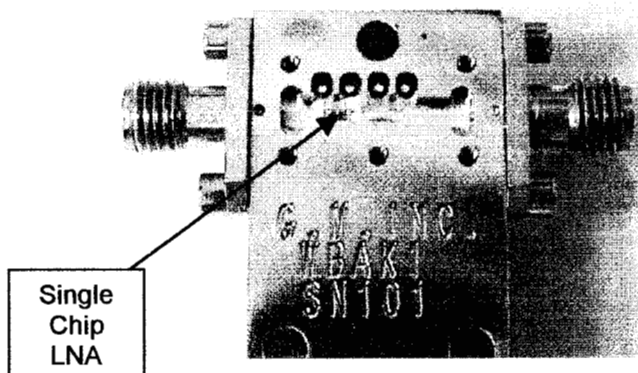


Figure 2 - Module with single chip MMIC LNA and measured noise temperature of the module at physical temperatures of 19K and 80K.

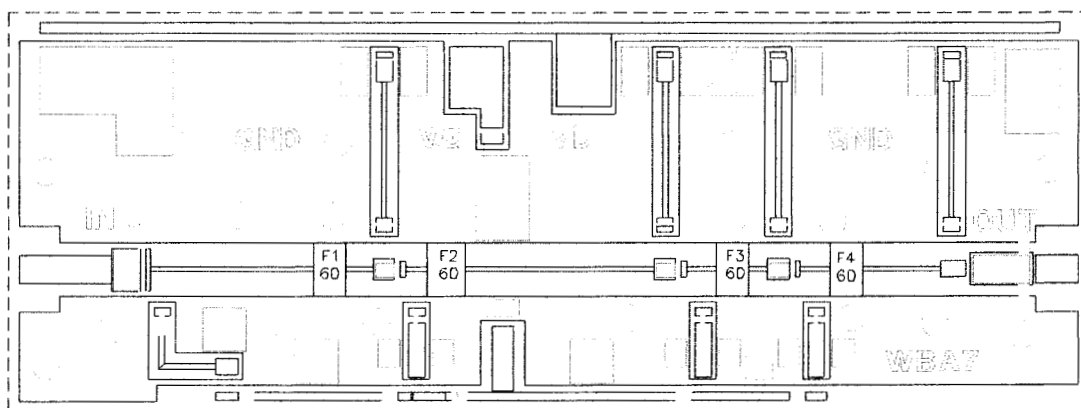


Figure 3 – Layout of 1-60 GHz low-noise amplifier. The chip size is 2 x 0.74mm and four 0.1 x 60 μ m InP HEMT's are utilized. The same basic design has been processed in both TRW and HRL foundries.

Measured WBA7M 5049

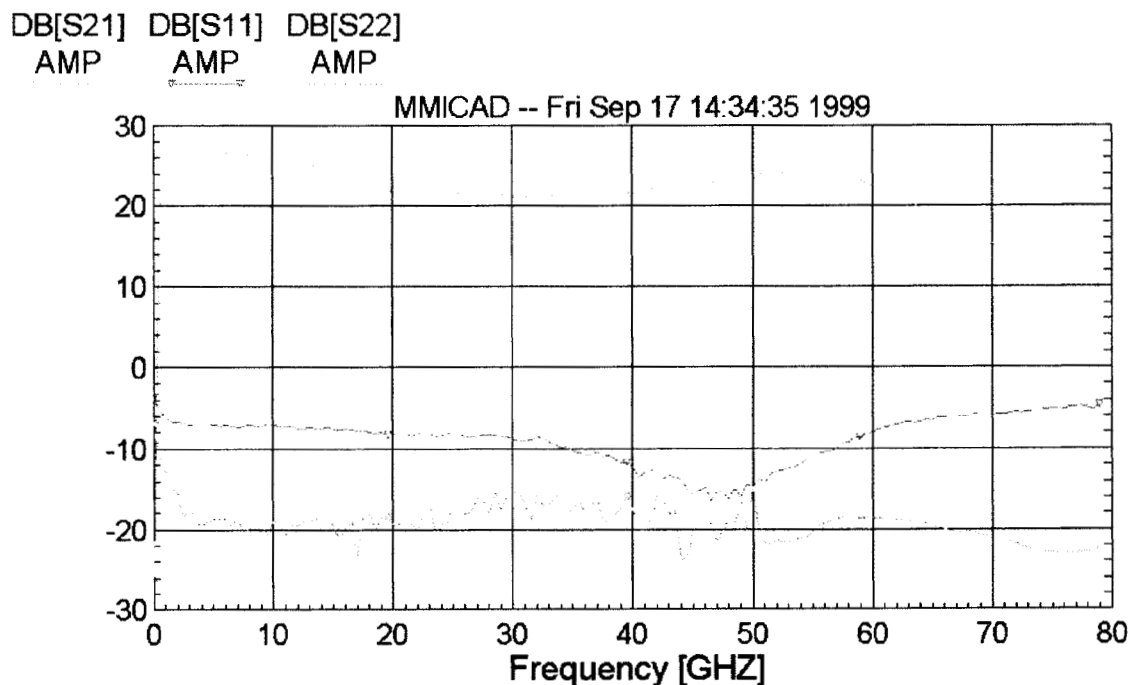


Figure 4 – Measured gain, input return loss, and output return loss for the 1-60 GHz wideband amplifier shown in Figure 3. Two versions of the amplifier have been fabricated; one with good NF and low input return loss, and another with data shown here, with an attenuator at the input to give a better match but with higher noise figure. The noise figure has not been measured at present but is estimated to be 3 dB for the unmatched amplifier and 8 dB for the matched amplifier.

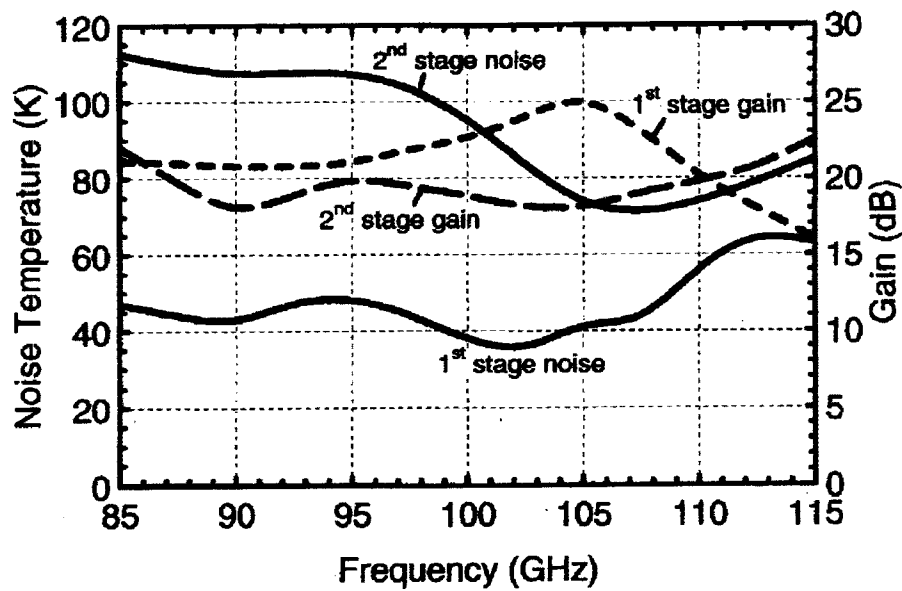


Figure 5 – Noise and gain at 20K for two InP HEMT low noise amplifiers used in the U. of Massachusetts 16-element focal plane array receiver [6]. The first stage is the 105LN1P fabricated at TRW and the second stage is an 86LN1 fabricated at HRL laboratories.

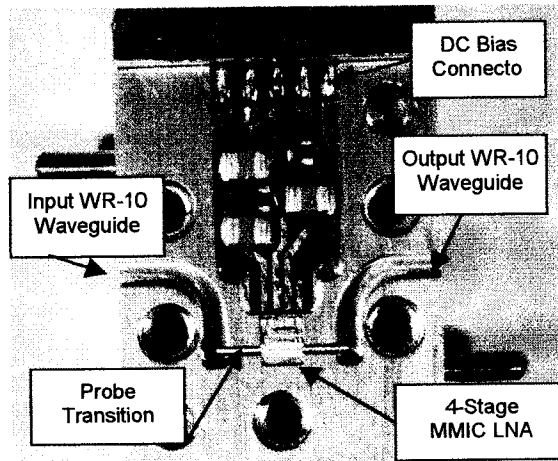


Figure 6 - Interior view of split-block module used to package either of the 4-stage MMIC's with data shown in Figure 5.